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Status of micro-hydrokinetic river technology in rural applications: A review of literature

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A B S T R A C T

Apparently, most hydrokinetic literatures mainly concentrate on large-scale technologies such as waves, tides and ocean current applications. This could be one of the reasons delaying the utilization of small-scale hydrokinetic river technology in rural areas. This paper therefore critically reviews the current status of micro-hydrokinetic river (MHR) technology for rural applications. Relevant research literatures based on developments, applications, design, operation as well as different MHR technologies involved in rural electrification projects have been reviewed. After conducting these reviews it has become clear that one of the key barriers hindering the employment of MHR technology in rural areas with access to flowing water is the lack of research demonstrating the technical, economic and environmental benefits of this technology compared to other rural electrification techniques. Studies that look towards the long-term perspective of techno-economic analysis inclusive of capital, maintenance and running costs computations need to be carried out promoting the interest in utilizing this technology. This paper will aid researchers to identify areas that need to improve as well as encourage public bodies to implement proper energy policies regarding the MHR technology usage in rural areas. It will also create awareness among site owners, investors, project developers and decision makers regarding the potential benefits of using this technology in rural areas especially in countries with little or no elevation.

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1. Introduction

The growth of climate change and electrical demand as well as rising diesel fuel prices are the key subjects encouraging the use of renewable technologies. Utilization of electrical energy plays an important role in economic growth and improvement of people's living standards. An ideal energy source should be renewable and should have minimal effect on environment [1]. It has been proved that one-third of the world's population does not have access to electricity, but does have access to moving water [2]. Majority of rural residents are very poor, with low living standards, limited education and little access to information. Despite the efforts in remote area electrification, progress and success rates remain low. Poor planning, lack of research and negligence are some of the factors contributing to the delay of rural electrification deployment [3].

To improve the living conditions of rural residents, provision of electricity is crucial. Small remote communities often require electricity supply for small loads such as lighting, refrigeration, communications etc. [4]. Solution towards rural electrification is made possible by means of basic approaches/techniques such as grid-extension, diesel generators or small-scale renewable energy systems. However, grid-extension to rural areas is considered uneconomical by many utility companies, due to the low consumption and poor load factors. This is certainly an unattractive supply option since most rural residents are poor and thus unable to finance electrical services [5].

Diesel-power generator (DG) has been the most popular option since it used to be the cheapest available option, particularly for low load applications [6]. It can be used in many remote settlements, either for a single user or as part of a local distribution network. In addition, it is safer, durable and also requires less maintenance. Nevertheless, DG approach continues to be more unsustainable for rural residents due to further increase of petroleum prices and difficulties in transporting the fuel to remote places.

Renewable technologies (biomass, wind, solar, hydro and geothermal) are offering clean and reliable energy to reduce greenhouse gas emission that lead to global warming while saving money and creating jobs. They provide a cost-effective source of electricity in rural areas where distances are large, populations are small, and demand for energy is low [7]. Small-scale renewable technology is a very good option for supplying electric power to isolated rural areas [8].

For remote areas situated in close proximity to flowing water, micro-hydro system is the most economical and reliable option for generating electric power [9]. It can compensate non-continuous availability of many renewable energy resources such as wind and solar. Among different renewable energy technologies, hydropower generation (large and small scale) holds prime position in terms of contribution to the world's electricity generation [9–12]. Large-scale hydropower stations are equipped with large dams and huge water storage reservoirs. As a result they received considerable criticism due to their negative environmental impact [10,11,13].

Small-scale hydropower is one of the most economical and environmentally friendly technologies to be considered for rural electrification projects. It can be a very good complement to a solar power system, as it produces electricity for 24 h a day as long as the running water is available. It is a much more concentrated energy resource than either wind or solar power [9]. It is often classified by the power generation potential as shown in Table 1 [8].

Table 1
Small-scale hydropower classification by power generation.

Classification	Size in kW
Small hydro	1000–30,000
Mini hydro	100–1000
Micro hydro	< 100

A conventional micro hydropower station essentially needs water to be diverted from the stream and brought to the turbines without losing the elevation/head. Compared to DG, conventional micro-hydro is characterized to have high initial capital cost and very low running costs [14]. However, the disadvantage of using conventional small-scale hydropower is that, in most cases it is obtained from run-of-river plants that lack the reservoir capacity to store water [9]. As a result, a backup electricity supply will be required due to seasonal variations resulting in severe reduction of firm output power, depending on the site hydrology [8,15].

Apart from conventional hydropower generation, hydrokinetic is a new category of hydropower energy that generates electricity by extracting kinetic energy of flowing water instead of potential energy of falling water. It shares lot of similarities with wind turbine systems in terms of the physical principles of operation, electrical hardware, and variable speed capability for optimal energy extraction [16]. But because water is almost 800 times denser than air, hence hydrokinetic turbines extract enough energy even at low speed [17–20]. It generates electricity without the need of building dams and other costly projects [21–24].

In addition, this technology is becoming more attractive among other renewable energy sources due to its high energy density, good predictability and minimal environmental impact [25–27]. Many remote villages and farms might be situated in close proximity to rivers with little or no elevation. In such cases it is impossible to use the conventional micro-hydro generation [28]. This simply depicts that there is theoretically huge number of potential sites available for hydrokinetic technology compared to the traditional hydropower generation [29].

This technology is still in the development stage and there is a lack of application especially in rural areas with reasonable water resources. It is hoped that the information presented in this paper can be useful for a better understanding of the benefits offered by this micro-hydrokinetic river (MHR) technology.

In order to aid with more development of this technology, it is of an urgent requirement to demonstrate its current status. Hence, through brief review of recent hydrokinetic river development studies for remote/rural electrification applications, this study aims to provide researchers/developers with more prioritized outlook of needed advancements. This paper will also be useful to site owners, investors, project developers and decision makers who are responsible for critical screening and approval of rural electrification programmes. It will facilitate permitting policies by regulatory agencies and promote project financing by financial institutions.

2. Hydrokinetic technology

Hydrokinetic energy is captured from waves, tides, ocean currents, the natural flow of water in rivers, or marine thermal gradients [1,30]. However, the scope of this paper is limited to applications in free-flowing rivers, since it is suitable for small-scale electricity generation [29,31]. Hydrokinetic or water current turbines, produce electricity directly from the flowing water in a river or a stream. The turbine blades would turn the generator and capture the energy of the water flow.

2.1. Operation principle

The amount of electricity that can be generated from this energy source is dependent on the volume and velocity of the

water resource. It can be installed in a flow with water velocity ranging from 0.5 m/s and above [13]. There are many concepts for harnessing this energy, but turbine has being the most common and proven one. Similar to wind energy converters, the total available power (Watt) captured by hydrokinetic turbine is dependent on the density, cross-sectional area, velocity cubed and turbine coefficient as shown in Eq. (1). The advantage is that the water is approximately 800 times denser than air [18]. This simply implies that the amount of energy generated by a hydrokinetic turbine is much greater than that produced by a wind turbine of equal diameter under equal velocity of wind and water.

$$P_a = \frac{1}{2} \times A \times \rho \times V^3 \times C_p \tag{1}$$

where A is the turbine area (m^2), ρ the water density (1000 kg/m^3), V the water current velocity (m/s) and C_p the turbine power coefficient or efficiency which is 16/27 = 0.592 (theoretical maximum power available)

Similar to wind turbine, the power coefficient (C_p) denotes that the hydrokinetic turbines can only harness a fraction of the total kinetic power due to losses entailed. This coefficient is limited to 16/27 = 0.59 by the well-known Betz law [32,33]. But a small-scale river turbine has its own losses which will reduce the power coefficient to around 0.25. The upper limit is for highly efficient machines with low mechanical losses.

2.2. Turbine blades sizing

Hydrokinetic turbines are zero head turbines. They generate electricity using kinetic energy of natural water resource by making use of different types of rotors. Turbine sizing starts by first estimating power required by remote home [34]. The radius of the turbine blade can then be calculated from Eq. (2). The turbine power coefficient (C_p) is a nonlinear function of the tip speed ratio and pitch angle. However, for a hydrokinetic turbine with fixed pitch angle, the power coefficient is only determined by the tip speed ratio [16].

$$P_a = \frac{1}{2} \times \pi \times r^2 \times \rho \times V^3 \times C_p(\lambda, \beta) \times \eta_D \tag{2}$$

Wher, r is the radius of the turbine (m), η_D the efficiency of the drive train (e.g. generator, gearbox, etc.), λ the tip speed ratio and β the pitch angle (degrees) of the turbine.

The tip speed ratio (λ) is expressed as

$$\lambda = \frac{w \times r}{V} \tag{3}$$

where w is angular velocity of the turbine in (rad/s).

The relationship between the power coefficient, tip speed ratio and pitch angle is expressed as in Eq. (4).

$$C_p(\lambda, \beta) = c_1 \left(\frac{c_2}{y} - c_3 \times \beta - c_4 \times \beta^x - c_5 \right) \times e^{C_6/y} \tag{4}$$

The values of the coefficients C_1 to C_6 and x depend on the type of a turbine used.

2.3. Resource assessment

A compelling aspect of power generation from hydrokinetic technology is the predictability of the resource, which is generated by the gravitational pull of the sun and moon on the earth's oceans [35]. Immediately the currents at a site have been well characterized it is possible to make accurate predictions of the electricity that would be generated by an array of turbines. The direction of the currents helps to determine an optimal device orientation or type of device suitable for a site [36]. Through the varying velocities and water levels that can be encountered in any river when the energy is extracted, the data needed for the development of a hydrokinetic energy generation site become highly site specific [37]. To date, such assessments of hydrokinetic resources are limited, but nevertheless increasing. Also the global river databases are not readily usable for river energy analysis.

Lalander [38] showed that the models that so far have been used for estimating the resource in Dal River, Norway have been shown to be uncertain since they do not account for the fact that the velocities and the water levels are altered when energy is extracted. A channel in the Dal river, the Söderfors channel, is situated downstream a hydropower plant and was simulated with the numerical model MIKE. To demonstrate these variations, water level alteration due to turbines was simulated. It was shown to be a lot less than the water level alteration caused by the level change in the downstream lake. Velocity profiles measured at several different locations were used to estimate how the power coefficient was changed. Four turbine configurations were studied and it was shown that changes in the power coefficient were prominent only for a vertical shear profile with a strong gradient.

Briand and Ng [39] presented the approach developed by RSW (consulting engineers) firm to design a hydrokinetic site in the riverine environment, from resource assessment to detailed engineering design. This approach focuses on the development of hydrokinetic sites from the first stages of identifying river reaches with potential (resource assessment, ranking sites from most interesting to least interesting) to hydrologic, hydraulic, environmental, and economic studies (pre-feasibility and feasibility studies) and finally to detailed engineering design of a prototype and of an eventual turbine farm.

Duvoy and Toniolo [40] developed a new tool called HYDROKAL for hydrokinetic resource assessment in rivers. This tool includes a user-defined efficiency factor to account for turbine efficiency, which is fundamental for estimating the energy that could be harvested from the river. For each river cross section along the computational domain, maximum velocity and specific discharge are identified to assist in estimating the stability of the river reach and, thus, the feasibility of installing an in-stream turbine. A Python script was also developed to export the results from HYDROKAL to CCHE2D. HYDROKAL is applied to a reach of the Tanana River at Nenana, Alaska, USA.

3. Micro-hydrokinetic river technologies

3.1. Turbines

Several hydrokinetic conversion concepts have been developed but turbine is the most used one. For rivers or artificial waterways this turbine technology is generally referred as river current turbines (RCT) or river current energy conversion system (RCECS) [41,42]. RCT are generally in the range of 1–10 kW [43]. RCT are configured either as horizontal or vertical axis turbines similar to those developed for wind generation.

The two most common small-scale hydrokinetic turbine concepts are axial-flow turbine and cross-flow turbine [44]. The selection of turbine type depends on the flow type, velocity and desired output of the system [13]. Axial-flow (alternatively called horizontal axis) turbines have axes parallel to the fluid flow and employ propeller type rotors. Various arrangements of axial-flow turbines are shown in Fig. 1. Inclined axis turbines (i) have mostly been studied for small river energy converters. Other axial-flow turbines (ii, iii and iv) are mainly used for extraction of ocean energy and are similar to wind turbines in terms of design and structural point of view [13,41,44,45].

The cross-flow turbines (Fig. 2) have rotor axes orthogonal to the water flow but parallel to the water surface. They can be

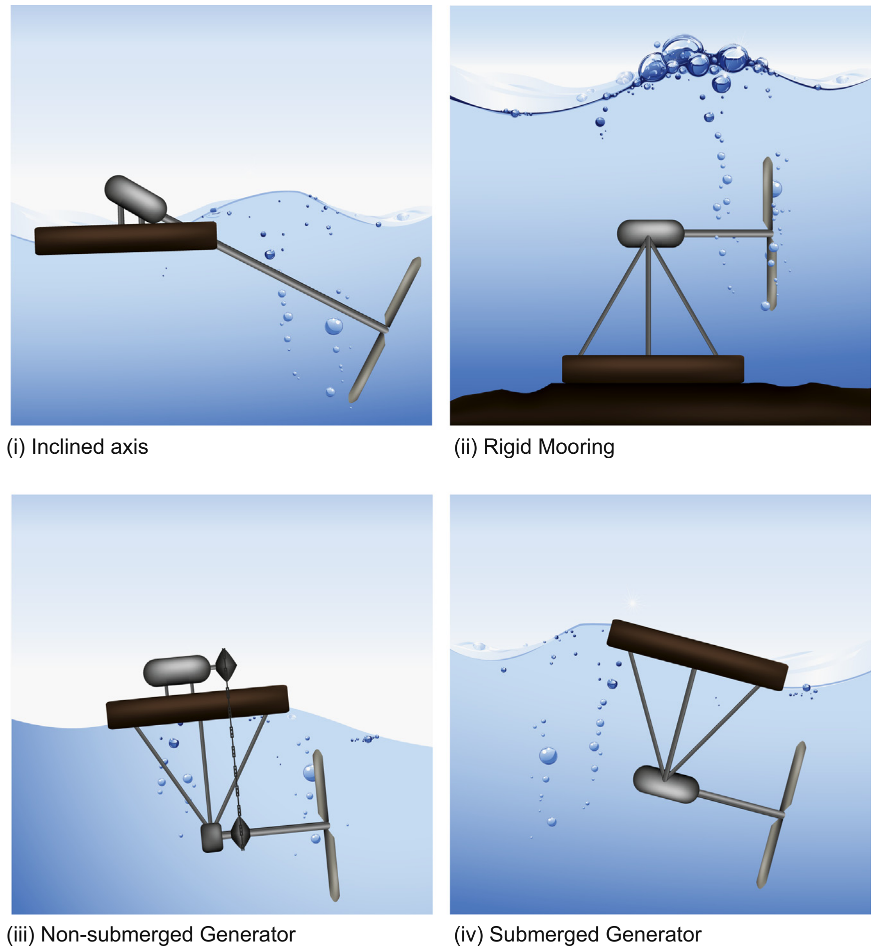

Fig. 1. Horizontal axis turbines by [41,44].

divided into vertical axis (*axis vertical to water plane*) and in-plane axis (*axis on the horizontal plane of the water surface*). The in-plane turbines (*i*) are generally drag based devices and said to be less efficient than their lift-based counterparts.

In the vertical axis domain (*ii*, *iii*, *iv*, *v and vi*), Darrieus type turbines are common in river energy applications [43]. Straight bladed Darrieus turbines (H-type or Squirrel Cage type) might be considered as a viable option for hydro applications [43,44].

The technical advantages and disadvantages associated with horizontal and vertical turbines are shown in Table 2.

Anyi and Kirke [46] reviewed works involving small axial flow hydrokinetic turbines specifically for generating electrical power for off-grid remote communities and suggested improvements to overcome a major problem. Turbines mounted on pontoons or suspended using pivot arms from river banks or from jetties are reported able to produce about 1–2 kW of electrical power suitable for remote homes. A deflection device and system that uses rotor with swept-back blades was suggested to overcome debris problem. By making the system resistant to debris, efficient axial flow turbines could be used practically in tropical rivers.

Kirke [47] reviewed the recent developments in open flow current turbine design and explored some potential advantages of ducted or “diffuser-augmented” current turbines. These include improved safety, protection from weed growth, increased power output and reduced turbine and gearbox size for a given power output.

Van Arkel et al. [22] introduced a new type of kinetic hydro-power generator, ideally suited to relatively small shallow rivers and channels. The design utilizes rectangular hydroplanes (‘sails’) moving around the device. The device extracts energy from a flow of water using an elongated vertical axis turbine, where a series of sails are mounted between two belts at the top and bottom of the device, rotating in the horizontal plane. The concept would be ideally suited to relatively shallow rivers and channels, because it can be designed to fill more of the channel's cross-sectional area than the circular rotor of a standard marine turbine or array of turbines.

Birjandi et al. [48] investigated the macro-turbulent flow structures interaction with vertical hydrokinetic river turbine. The results aim to characterize flows in rivers to improve our understanding of the impact of turbulent inflow structures on hydrokinetic power generation, and to contribute to the optimization of vertical and horizontal axis hydrokinetic turbines. Furthermore, power spectrum measurements provided data to improve the fatigue lifetime estimation of vertical turbines, as the scale and intensity of turbulent structures can play an important role.

Kirke [49] carried out some tests on several helical and straight blade Darrieus type cross flow hydrokinetic turbines with and without variable pitch, with and without slatted diffusers. Variable pitch has been suggested to increase starting torque and efficiency, ducts to increase power output and helical blades to produce smooth torque. These tests were performed at velocities ranging from less than 1 m/s and up to 5 m/s in Nerang River of Australia and Campbell River in Canada. The helical blades made little difference to efficiency and starting torque but the turbine ran smoothly, unlike that with fixed pitch straight blades. The diffuser increased power output by a factor of up to 3 compared to the same turbine without a diffuser, but this augmentation factor was

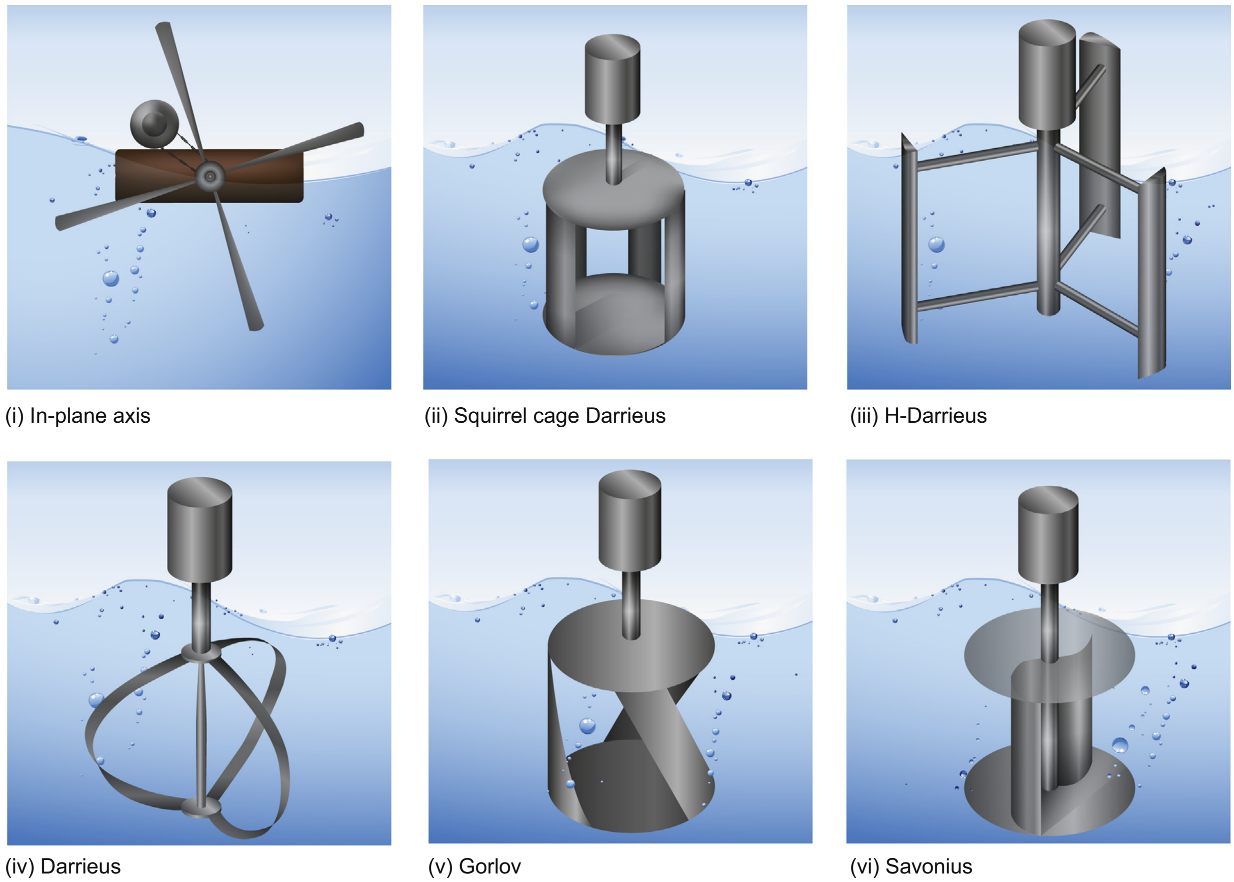

Fig. 2. Vertical axis turbines by [41,44].

Table 2
Technical advantages and disadvantages of horizontal and vertical turbines.

Turbine configurations	Advantages	Disadvantages
Horizontal axis turbines	Self-starting capability [41,44]	High generator coupling cost due to underwater placement [41,44]
	Gearbox elimination possible through the use of a duct [16]	Ducts cannot be easily used for floating purpose [41]
	Optimum performance is achieved at higher rotor speed (marine/tidal conversion), this ease with the reduction of reduced gear coupling [41]	
	Active control by blade pitching allows greater flexibility in over speed protection and efficient operation [41]	
Vertical Axis Turbines	Low generator coupling costs due to placement above water [1,16,41]	Due to low starting torque, may require starting mechanism [41,43,44]
	Emits less noise due to reduced blade tip losses [41]	Generates torque ripple in the output [41,43,44]
	Can rotate unidirectional even with bi-directional fluid flow [13,41,44,45]	Lower efficiency [41,43–45]
	Cylindrical shape of the Darrieus turbine allows convenient mounting of various ducts [41]	
	More suitable for operation under shallow channel with varying water velocity and shallow stream with limited water flow rate [1,41]	

not achieved in all tests, and the cost-effectiveness of the diffuser is doubtful. These findings suggest that variable pitch cross flow hydrokinetic turbines should be further investigated.

3.2. Generators

Electric generators are devices that convert mechanical energy into electrical energy. Generators can generally give direct current (DC) or alternating current (AC). Choosing a generator for specific application is governed by number of factors such as the prime mover speed, required output power, range of operation and use. Hydrokinetic plants use the same generators as used by conventional hydro and wind power generation. Generally, the two commonly used generators in wind and hydrokinetic turbine systems are synchronous and induction generators [16]. From Table 3 it can be seen that permanent magnet synchronous generator (PMSG) is suitable for small-scale river-based hydrokinetic systems compared to induction generator.

3.2.1. Synchronous generators

This type of generator runs at a constant speed. They are equipped with a DC electric or permanent magnet excitation system. The permanent magnet excitation type has cornered the

Table 3
Advantages and disadvantages of synchronous and induction generators for small-scale generation.

Generator type	Advantages	Disadvantages
Synchronous generator (permanent magnet type)	No extra field excitation needed Have higher efficiency due to direct drive permanent magnet Can operate at slower speeds, hence allowing the direct-drive train without gearbox Lower maintenance costs due to absence of brushes High power density [16]	Frequency inverter and rectifier needed during variable speed To get a suitable frequency at low speed, it requires large number of poles and an increase in turbine radius
Induction generators	Can supply constant voltage and constant frequency at variable speeds [16] High reliability [1] Cheap and simple to design [1]	Lower efficiency compared to permanent magnet synchronous generator Needs speed faster than the synchronous speed. At low river flow speeds, a need exist for speed increaser

market in small-scale hydro and hydrokinetic energy conversion systems due to its simplicity, high reliability, low noise and high power density [16]. It can run isolated from the grid and produce power since excitation is not grid-dependent.

To work with variable speed, it includes a frequency inverter, composed by a rectifier. The rectifier transforms the slip frequency ranges and currents into DC voltages and currents, and an inverter transforms DC voltages and currents in synchronous frequency voltages and currents [50].

3.2.2. Induction generators

Induction generators are the most common types of electrical generators used in stand-alone power generation systems. This type of a generator is also favoured for small-scale electricity production due to its simplicity, robustness, small protection capacity and small size per generated kW [51]. Unlike the synchronous generators, induction generator does not require external DC source [52].

Induction generators such as doubly-fed induction generators and squirrel cage induction generators are available [16,53]. The commonly used induction generators are squirrel cage rotor types since they are brushless. Despite the lower efficiency than an equivalent PMSG and a need to run at a more or less fixed speed, they are very attractive for small-scale electrification.

Induction generators rely on a connection to an outside source of power, i.e. the electricity network, to establish and control the rotating magnetic field [54]. However, when using induction generators in isolated operation i.e. for off-grid operation, the excitation is conducted through a parallel connection of a capacitor bank [55].

Thomas, et al. [56] designed an efficient low speed permanent magnet generator to be utilized for low tidal current velocities, in the order of 1 m/s. This generator can be suitable for low speed river applications as well since it efficiently operates at varying speeds and eliminates the use of gearbox to reduce transmission losses. It generates 5 kW of power at a water current velocity of 1.5 m/s.

3.2.3. DC generators

DC generator is a machine that converts mechanical energy into direct current electrical energy. DC generators are equipped with a DC electric or permanent magnet excitation system. DC generators are generally expensive. Hermann [27] demonstrated that using a DC generator to charge batteries via small micro hydropower plants is not a viable solution for rural electrification. Their usage is restricted due to low transmission efficiency. The main reason being due to the low generated voltage, electrical transmission will be difficult. AC generators are the most suitable ones for providing electricity to remote areas [1].

Table 4
Comparison of technical and economical results.

Costs	HKP	PV	Wind	DG
Capital ($)	Low	High	High	Lower
Replacement ($)	Lowest	High	Low	Lower
O&M ($)	Lowest	High	Low	Lower
Fuel ($)	Zero	Zero	Zero	High
Total NPC ($)	Very Low	Higher	High	Highest
COE ($/kWh)	Very Low	Higher	High	Highest
Grid extension (km)	Very Low	Higher	High	Highest

4. Techno-economic analysis

Rural electrification processes are being carried out in many developing and under-developed countries with the help from developed countries or from the governments through loan incentives or subsidy channels [57]. The majority of people living in rural areas are very poor. Hence, a need exist to bring the most affordable rural electrification option in order to alleviate poverty. Among different renewable energy technologies, MHR is simple to design and can be easily installed and maintained by local population at low cost if installed in remote and rural areas. Few studies have been done to prove technical and economic benefits of this technology.

Kusakana and Vermaak [29,58] investigated the possibility of using and developing hydrokinetic power to supply reliable, affordable and sustainable electricity to rural, remote and isolated areas of South Africa. The simulations where performed by means of the Hybrid Optimization Model for Electric Renewable (HOMER) software using the same load for each supply option. The aim was to compare hydrokinetic to the other supply options such as standalone PV, wind, diesel generator and grid extension line. The summary of technical and economical results is shown in Table 4 below. Based on the Net Present Cost (NPC), Cost of Energy (COE) and breakeven grid extension distance results it shows that hydrokinetic power (HKP) is the best option.

Kunaifi [59] evaluated the most cost effective option by harnessing energy from a combination of Darrieus Hydrokinetic Turbine (DHT) and different energy sources. The aim was to enhance the sustainability of rural electrification programs in Riau. HOMER simulation program was used. This software is not equipped with a free-flow river module. For hydrokinetic power simulation, the wind turbine module was used since it shares lot of similarities with the hydrokinetic turbine system. From the simulation results, it was found that the best hybrid technology to meet 100% load demand was the combination of PV, Hydrokinetic, Diesel, Battery and inverter.

5. Current companies and their technologies

Some companies have already developed hydrokinetic river technologies. Table 5 shows the list of companies and relevant technologies. Specifications such as minimum/maximum operating speed and maximum output power based on the types of the manufactured turbines are also shown.

6. Optimization of river current technology

With energy demands and costs increasing, improving energy efficiency of generation system is critical since it can have an impact on the reduction of greenhouse gases emission. Several MHR technology optimization techniques/methods based on cost and performance were studied.

6.1. Cost optimization

Anyi and Kirke [34] demonstrated that the construction of an optimum hydrokinetic turbine blade can be accomplished by using common tools, common materials and simple jigs.

The simplified method of blades construction allows it to be made in a remote village near to where it will be used and maintained. This will reduce the total cost of a turbine system significantly because by producing turbine components locally, the costly currency exchange and importation cost can be avoided. Furthermore local construction creates job opportunity which could help remote people financially.

6.2. Performance evaluation

Golecha et al. [66] carried out an experimental investigation on the performance improvement of modified Savonius rotor by providing a deflector plate on the returning blade side. The experiment was conducted to find the adequate configuration of the deflector plates on the returning blade side and advancing blade side. Results conclude that the deflector plate at its optimal position increases the coefficient of the power (C_p) by 50% for a single-stage modified rotor. The performance deteriorates by increasing the number of stages. This suggests that the use of a single stage modified Savonius rotor is better compared to two and three stages. The summary of the performance tests results of different Savonius rotor configuration stages is shown in Table 6 below.

Golecha et al. [67,68] studied the performance of modified Savonius water turbine with two deflector plates. The objective of this study was to identify the optimal position of the deflector plate placed upstream to the flow which would increase the power generated by the rotor. The results suggested that the two deflector plates placed at their optimal positions upstream to the flow increase the maximum coefficient of power (C_{pmax}) to 0.35 as opposed to 0.21 with single deflector plate on the returning blade side and 0.14 without deflector plate. This shows the promise of using deflector plates on both advancing blade side and returning blade side to increase the performance of the modified Savonius rotor. The summary of the deflector optimum position tests results is shown in Table 7.

Batten et al. did the design of a floating free stream energy converter in [69]. In [70] they analyzed the potential of using the floating body structure to increase the efficiency of this free stream energy converter. It was proved that the use of the separators and scoops can be a cost effective method of increasing the power output. From the results, it was shown that the addition of a 90° separator caused the generated power to increase by almost 100%. For the 45° separator the increase in generated power was not so large. The inclusion of scoop to that 45° separator increased the generated power to almost that of the 90° separator. The detailed efficiency test results on the effect of the separator and scoop are shown in Table 8 below. Floating water wheels may be a viable option for small-scale electricity generation in remote locations due to its simplicity and low costs.

Table 6
Coefficient of power improvement of different modified Savonius rotor configuration stages.

No. of stages of modified Savonius rotor	% C_p improvement
Single stage	50
Two stage (phase shift of 0°)	42
Two stage (phase shift of 90°)	31
Three stage	15

Table 7
Summary of the deflector optimum position tests results.

No. of deflector plates	C_{pmax}	Tip speed ratio
Zero deflector plate	0.14	0.7
Single deflector plate (*on the returning blade side*)	0.21	0.82
Two deflector plates (*additional deflector blade on advancing blade side*)	0.35	1.08

Table 5
List of companies and associated technologies.

Manufacturers	Device name	Turbine type	Min./Max. speed	Power output
Lucid Energy Pty., Ltd. (USA) [28]	Gorlov Helical turbine	Helical Darrieus cross-axis	(0.6 m/s)/no limit	Up to 20 kW, depends on size
Thropton Energy Services (UK) [60,61]	Water current turbine	Axis flow propeller	(0.6 m/s)/depends On diameter	Up to 2 kW at 240 V
Tidal Energy Pty., Ltd. (Australia) [62]	Davidson–Hill Venturi (DHV) Turbine	Cross flow Turbine	Min. 2 m/s	From 4.6 kW
Seabell Int. Co., Ltd. (Japan) [63]	Stream	Dual, cross-axis	(0.6 m/s)/no limit	0.5–10 kW models
New Energy Corporation Inc. (Canada) [64]	EnCurrent Hydro Turbine	Cross-axis	Max. 3 m/s for maximum power	5 kW (and 10 kW)
Eclectic Energy Ltd. (UK) [65]	DuoGen-3	Axial flow propeller	Min. (0.93 m/s) /(4.63 m/s) max.	8 amps at 3.09 m/s
Alternative Hydro Solutions Ltd. (Canada) [61]	Free-stream Darrieus water turbine	Cross-axis	(0.5 m/s)/depends on diameter	Up to 2–3 kW
Energy Alliance Ltd. (Russia) [60]	Sub-merged hydro unit	Cross-axis	Min 3 m/s	1–5 kW (and > 10 kW)

Table 8
Effect of separator and scoop on the maximum efficiency.

Condition	Efficiency (based on blade area) (%)
No Separator	41
90° Separator	87
45° Separator	70
45° Separator and Scoop	81

7. Conclusion

This paper has investigated the current status of MHR technology in rural applications. This study was undertaken to simplify the identification of research gaps within the use of MHR technology for rural electrification. This was done by reviewing relevant literatures based on the developments, applications, designs, operations as well as different MHR technologies involved in rural electrification projects. This study has found that generally there is a lack of research studies revealing technical, economic and environmental benefits of this technology compared to other rural electrification methods. In general, therefore it seems that lack of such studies is a challenge hampering the application of this technology in rural areas.

This study attempts to improve the interest in the utilization of MHR technology. Researchers will identify critical areas that need further development for rural applications. This paper will also be useful to site owners, investors, project developers, policy and decision makers who are responsible for critical screening and approval of rural electrification programmes. Hence, this will contribute to the vulgarization as well as the application of this technology within rural areas not served by the grid and where adequate water resource is available.

Since most published studies tend to focus on large-scale hydrokinetic projects, we call for future MHR research efforts to be directed in the following areas:

- Optimal sizing and operation control;
- Reliability, sustainability and efficiency;
- Techno-economic and environmental analysis of this technology compared to other rural electrification supply options,
- Policies supporting the development and deployment of hydrokinetic power.

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